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Tailoring Leadership to the Phase-Specific Needs of Large Scale Research Infrastructures

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TAILORING LEADERSHIP TO THE PHASE-SPECIFIC NEEDS OF LARGE SCALE RESEARCH INFRASTRUCTURES

A PREPRINT

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ABSTRACT

'Large Scale Research Infrastructures' (LSRIs), a subcategory of megaprojects which incorporate a characteristic of a high or 'super high' level of technological uncertainty, are often undertaken as cooperative projects with long lead times by one or more national governments. A lack of research into the effect of the LSRI project's lifecycle on the research organisation is apparent, particularly when scientists and engineers exercise freedom to organise the project directly. Two case studies used senior leadership selection as proxy for the LSRI project lifecycle using a contingency theory framework. These were the Tevatron (Fermi National Accelerator Laboratory, USA) and the Large Hadron Collider at the European Organisation for Nuclear Research (CERN). This LSRI lifecycle is mapped onto lifecycles used in theory and in policy. Previous research did not detect that these projects become institutionalised, so influencing the selection of new research organisation senior leadership according to its needs at that stage of its lifecycle. This represents something of a novelty as most contingency theory work is theoretical with few attempts to use it as a conceptual framework for empirical evidence. The findings indicate a second new understanding, that while the literature characterises a leadership style transition from democratic to authoritarian as the project progresses, LSRIs exhibit a reverse transformation, probably as a product of the characteristically high level of organisational technical competence. The construction of LSRIs maps better onto the traditional project lifecycle and the National Science Foundation's large facility lifecycle than onto other lifecycles. There is a policy opportunity to commission a 'generational survey' upon the completion of an LSRI, to understand the characteristics of the 'next big machine'.

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Keywords LSRI · research infrastructure · megaproject · project management · lifecycle · leadership

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1 Introduction

This article examines the tailoring of senior leadership selection of research organisations to meet the phase-specific needs of Large Scale Research Infrastructures (LSRIs). LSRIs have been defined as "large scientific instrumentation, facility, and equipment clusters that require large investments and complex engineering efforts" (D'Ippolito and Rüling, 2019). But there is often some debate regarding scope as some funders, such as the National Science Foundation (NSF) in the United States, include human capital within the research infrastructure remit and other funders, such as the European Strategy Forum on Research Infrastructures (ESFRI), do not. These LSRIs are often extremely large facilities with construction budgets in the billion US dollar range: they are frequently organised as international collaborations due to the necessary scale of investment being beyond the funding capacity of any single national research system (Jacob and Hallonsten, 2012). The study of the field of LSRIs is still an emerging body of knowledge. The relative lack of established conceptual frameworks for examining LSRIs creates certain conceptual challenges. Therefore, this paper draws upon the relevant literature relating to megaprojects and technologically uncertain projects to locate LSRIs as a subcategory of megaprojects that incorporate a high or 'super high' level of technological uncertainty (Shenhar and Dvir, 1996; Flyvbjerg et al., 2003).

Other authors have undertaken significant work to examine different facets of research infrastructures and experimental collaborations using such facilities (D'Ippolito and Rüling, 2019); these include the wider economic impact of LSRIs (Autio et al., 1996, 2004), historic narratives (Hermann et al., 1987a,b; Krige et al., 1997; Hallonsten, 2011; Hoddeson et al., 2008; Heinze et al., 2015b; Riordan et al., 2015; Heinze et al., 2015a, 2017) and some evaluation exercises (Irvine and Martin, 1984; Martin and Irvine, 1984a,b). Yet, despite the prominence of LSRIs in the public sphere, their consumption of significant public funds, and the well-established policies for managing the construction of such facilities in the US and Europe (ESFRI, 2018; NSF, 2019), the literature lacks a cohesive conceptual framework concerning the management of LSRI construction projects by the host organisation and whether the project influences the host. It is therefore apparent that there is a gap in knowledge in terms of understanding senior leadership of research organisations that these LSRIs are based in. The first two research questions are linked to one another - **"do these LSRIs fit established lifecycle models?"** and **"if so, which model provides the best fit?"**. The answers to these two questions will allow identify the phases of an LSRI project and understand which of the lifecycle models offers the most appropriate framework. It also provides the opportunity to clarify the links between theory, policy, and practice. A third question examines how these phases influence leadership and is **"how does leadership adapt as the project moves through its lifecycle?"**.

The research examined the construction of two large scale research infrastructures – the Tevatron at Fermi National Accelerator Laboratory (hereafter referred to as 'Fermilab') in the United States and the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN) in the Franco-Swiss border region. The dataset draws on archival and interview research with participants representing a broad cross section of the laboratory and experimental communities for each LSRI. The results demonstrate that the LSRI project came to dominate both laboratories to such an extent that senior leadership selection was heavily influenced by the needs of the project at that phase of its lifecycle. This LSRI lifecycle does not necessarily map onto the lifecycles used by policymakers. As a result, this article identifies an opportunity to improve current policy by capturing how the research community assesses its own future needs[2] at the end stage of an LSRI; current policy does not capture community practices and finds itself having a time scope that is both too short to produce meaningful strategic change or too long to be actionable.

The remaining sections of this article are structured as follows: Section 2 examines the relevant literature for understanding and categorising LSRIs as a subcategory of the megaproject domain with an additional characteristic of a high or very high level of technological uncertainty and the relevant leadership literature. Section 3 outlines the methodology used for this research. Section 4 lays out the research findings from the two case studies individually and then as consolidated findings. Section 5 discusses these findings in relation to the literature examined in Section 2 before the conclusion in Section 6.

2 Literature Review

This section examines the most relevant bodies of literature related to large scale research infrastructures, project lifecycles used in theory and in policy, and the megaproject literature.

[2]These have various terms including 'community surveys' and 'roadmaps'.

2.1 Large scale research infrastructures (LSRIs)

The domain of LSRIs shares some overlap with 'Big Science' projects. However, while Big Science has a dual meaning in that, depending on context, it can refer to either large scale experimentation in the physical sciences or to the industrial production of scientific knowledge in the post-war period (Weinberg, 1961; De Solla Price, 1963). LSRIs can encompass a much broader range of facilities for the conduct of research (D'Ippolito and Rüling, 2019). These facilities are of significant policy interest due to their use for the investment of public funds into knowledge production (Florio et al., 2018).

The increasing prevalence of LSRIs, which often requires the application of organisation structure to research, is somewhat at odds with the historic perception of science as the product of the toil of a single individual (Blankenship, 1974). Concerns over research productivity and relative prioritisation have been issues for many years (Weinberg, 1961, 1962). Within LSRIs, leaders, who tend to be responsible for prioritisation within LSRIs, have frequently been the focus of research; indeed, this can be traced back to the early days of 'big science' (Hoddeson, 1992; Seidel, 1992; Heilbron and Seidel, 1989). Senior leaders remain key focal points for a laboratory (Hermann et al., 1987a; Hoddeson and Kolb, 2003). However, the scale of resources required to realise appropriate experimental aims has often made it unrealistic for a single national budget to bear, since overall construction budgets for research infrastructures now can exceed one billion US dollars (Collins, 2003; Florio et al., 2016; Mountain and Cohen, 2018; **?**). Greater internationalisation has been one response to this issue (Peng, 2012; Shore and Zollo, 2015; Shore and Cross, 2015; Vincenzi and Shore, 2019).

Most of the literature examining LSRIs tend to examine the topic in terms of research evaluation. One stream of work that can inform some of the issues raised by LSRIs is a series of articles from Martin and colleagues, which seek to evaluate big science laboratories (Martin and Irvine, 1984a,b; Irvine and Martin, 1984). In addition, there are studies which examine the social structure of such collaborations (Boisot, 2011; D'Ippolito and Rüling, 2019), and the returns on investment to the wider economy (Autio et al., 2004; Castelnovo et al., 2018).[3]

One challenge for investigators of LSRIs is the criteria for inclusion – namely, the lower dividing point at which a research infrastructure is considered to have become 'large'? Although Qiao et al. (2016) proposed a definition of LSRIs which D'Ippolito and Rüling (2019) utilised, the precise inclusion criteria were unclear. The individual researcher therefore lacks external guidance in the definition of 'large'. In this situation the megaproject domain becomes particularly valuable, by setting the conceptual agenda and providing the necessary concrete guidance for inclusion and exclusion.

2.2 Categorising LSRIs within the megaproject domain

This section examines the relevant literature that helps to place LSRIs in a subcategory of megaprojects, specifically those that incorporate an additional dimension of a high or very high level of technological uncertainty, megaprojects are a specific kind of project that have a minimum overall budget of one billion US dollars (Flyvbjerg et al., 2003; Davies et al., 2009) . They generally conceived as infrastructure that will remove constraints to economic growth rather than being independent drivers of revenue; therefore, their true value cannot be captured with the application of traditional measures (Flyvbjerg et al., 2003). Examples of this project class include London Heathrow Airport Terminal 5 (Davies et al., 2009), the Oresund Bridge (Dimitriou et al., 2014), and the London Elizabeth Line[4] (Whyte et al., 2016). At this scale, projects exhibit certain common characteristics. These include firstly the substantial use of subcontracting as no single company will have the necessary capacity to supply all the required components for the final product. Secondly there are significant systems integration challenges of coordinating component manufacture across global supply chains and successfully integrating these components on-site at the right time. Thirdly, because of their consumption of significant public funds and their association with national prestige, megaprojects are inherently political (Flyvbjerg et al., 2003). National and occasionally supranational authorities are therefore often stakeholders and their management has been the topic of much work (Hughes, 1998; Floricel and Miller, 2001; Flyvbjerg et al., 2003; Hughes, 2004).

Since its emergence as a field, the organisation of megaprojects has also evolved to meet organisational and technical realities. The traditional model for the construction of megaprojects was for the client, usually a public body such as a government department, to create detailed system specifications, regardless of whether or not they had access to in-house technical skills essential to be able to comprehend the underlying principles (Davies, 2017). A frequent consequence was poor definition of systems that later required substantial amendment, thus incurring substantial cost increases (Davies and Mackenzie, 2014; Davies, 2017).

[3]It is noted that Hallonsten and Heinze (2013) examined organisational processes within national laboratories using a framework for institutional renewal in which long term changes amongst actors begin at the periphery before taking a central role whereas this article uses the project as the unit of analysis.

[4]Formerly known as 'Crossrail'

LSRIs and megaprojects differ in the structure of their delivery. Modern megaproject construction generally uses a client and delivery partner arrangement wherein the client broadly defines the goals and specifications of the systems and then invites tenders for the construction contract (Davies and Mackenzie, 2014; Davies, 2017; Davies et al., 2019). Although any organisation can bid individually, it is not uncommon for several organisations to pool their resources in a joint bidding venture (Davies, 2017; Davies et al., 2019). The client then selects the preferred delivery partner from among the pitches (Davies, 2017; Davies et al., 2019). The selected delivery partner will be expected to have the technical competence to define the systems and goals with much greater accuracy and detail than the client (Davies, 2017). In contrast, however, this model generally does not apply to LSRI projects. Many laboratories do have this technical competence available internally, and this permits many systems to be developed in detail at an early stage of the project.

Although many projects can be managed by using well-established methodologies (Pinto, 2012); when projects exhibit significant technological uncertainty, the applicability of these standardised methodologies is questionable due to the impact of the inherent uncertainty (Mcfarlan, 1981; Shenhar and Dvir, 1996).

2.3 Project lifecycles

As noted above, contingency theory pairs an appropriate leader to a situation (Fiedler, 1964); this offers the opportunity of repeating this process, substituting a new leader as the situation changes. That projects might exhibit common characteristics over their lifetime is well-embedded in both literature and practice (Thompson, 1997; Montgomery and Largent, 2016). There are three primary lifecycle paradigms that are particularly appropriate for this paper: these are the traditional project lifecycle (Frame, 1987), the Wheelwright and Clark (1992) model, and the Gluck and Foster (1975) model. The traditional project lifecycle model is frequently used in the literature and practice, primarily because of its wide applicability (Adams and Barnd, 1997; King and Cleland, 1997; Pinto and Slevin, 1988). It divides a project into four phases, starting with a conceptual stage which moves onto planning and execution and concluding with termination (King and Cleland, 1997). It is common practice for project managers to adapt their behaviours and attitudes to suit these shifting needs (Frame, 1987; Wheelwright and Clark, 1992).

Alternative project lifecycle models relevant to this work do exist. Within the literature, significant work can be divided into documents looking at more traditional projects with clearly defined beginnings and ends to projects that seek to develop new mass-produced products with production included in the lifecycle. There is also a more normative body of project management work where the results can be very readily applied by practitioners although there is still academic utility in these works (Gluck and Foster, 1975; APM, 2015; APM and PwC, 2019). Within the product development literature, the work of Wheelwright and Clark (1992) although relatively mature is still frequently utilised as a conceptual framework within the literature (Beauregard et al., 2016; Tiedemann et al., 2019; Kavadias and Ulrich, 2020). Equally, from the more practitioner-focussed domain, the work of Gluck and Foster (1975) is also prominent within the literature (Johnson et al., 2009; Brattstrom et al., 2018; Johnson and Filippini, 2013). Notably, both Wheelwright and Clark (1992) and Gluck and Foster (1975) focussed on product development and classified its lifecycle from research through to final production. However, there is some debate concerning the exact structure of these two product development models (See Table 1 for a visual example mapping the models onto one another). Both Wheelwright and Clark (1992) and Gluck and Foster (1975) agree with Frame (1987) that product development resembles a traditional project in that managers must focus greater attention on the project during the final stages than at the beginning, despite the issue that at the late stages, a project is likely to have acquired greater momentum and inertia, thus becoming harder for a leader to affect the final state without incurring substantial costs. The shifting role of organisational leadership in is considered below in Section 2.4.

Within the policy domain there have been acknowledgements that research infrastructures advance through common lifecycles in a similar pattern, notably from the National Science Foundation (NSF) and the Department of Energy (DOE) in the United States and the European Strategy Forum for Research Infrastructures (ESFRI) (ESFRI, 2018; NSF, 2019). Close examination reveals that, although NSF, DOE, and ESFRI use different terminologies, their lifecycles do seem to be rather similar. One notable difference relates to the final phases, described as 'Divestment' and 'Termination' phases by NSF and ESFRI respectively. The 'Divestment' phase indicates that it is possible to include an older machine in the supporting infrastructure of a new one, whereas the term 'Termination' does not. It is also noteworthy that ESFRI (2018) has identified that "...the set of skills required by an RI [research infrastructure] may change markedly during its lifecycle", although the document failed to provide an elaboration as to how these skill requirements might change. This suggest that there may be a gap in policy understanding of how leadership changes during a project lifecycle – a gap that this article fills.

Despite these well-developed lifecycles used in industry and in policy, the role of leadership as a means of achieving these goals is less well-understood. Section 2.4 below provides an overview of the relevant generalised leadership

Table 1: A summary of the development project phases proposed by Wheelwright (1992) and Gluck and Foster (1975) respectively mapped onto the traditional project lifecycle and lifecycle models used by NSF, DOE, and ESFRI

<table>
<tr><th>Project lifecycle</th><th>Wheelwright (1992) model</th><th>Gluck and Foster (1975) model</th><th>Large facility lifecycle (NSF)</th><th>ESFRI lifecycle</th><th>Typical DOE acquisition management system</th></tr>
<tr><td>Conceptual</td><td>Knowledge acquisition</td><td>Study</td><td>Development</td><td>Concept development</td><td>Initiation</td></tr>
<tr><td>Planning</td><td>Concept investigation</td><td rowspan="2">Design</td><td rowspan="3">Design</td><td rowspan="2">Design</td><td rowspan="3">Definition</td></tr>
<tr><td rowspan="3">Execution</td><td>Basic design</td></tr>
<tr><td>Prototype building</td><td>Development</td><td>Preparation</td></tr>
<tr><td>Pilot production</td><td>Preproduction</td><td rowspan="2">Construction</td><td rowspan="2">Implementation</td><td>Execution</td></tr>
<tr><td>Termination</td><td>Manufacturing ramp-up</td><td>Production</td><td>Closeout</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>Operation</td><td>Operation</td><td rowspan="2"></td></tr>
<tr><td>Divestment</td><td>Termination</td></tr>
</table>

literature and looks and how leadership can be harnessed within project lifecycles and similar large high-technology projects to LSRIs.

2.4 Leadership paradigms

The leadership literature describes two broad paradigms into which most theory can be organised. The first, the style paradigm, divides leaders into two discrete categories based on the characteristics which they display (Bass, 1990). Leaders could theoretically shift their classification by changing behaviours to fit the new needs of an evolving situation (Bass, 1990). The second, the evolutionary paradigm, starts from the premise that leaders were born great and that research should chart the development of these great people to replicate these conditions for future leaders. From this evolutionary paradigm, the concept of contingency theory is more applicable to this work.

2.4.1 Style paradigm

Although very many potential leadership styles have been identified in the literature, most of it refers to five primary styles, being transformational, transactional, authoritarian, democratic, and laissez-faire leadership (Bass, 1990).

Transformational leadership is often idealised in the literature, and, in popular culture, such leaders tend to be highly charismatic and articulate a vision in terms of basic human values such as truth and high moral standards (Bass, 1990; Bass and Avolio, 1993; Kirkpatrick and Locke, 1996; Tracey and Hinkin, 1998; Raziq et al., 2018; Zaman et al., 2019). This vision acts as a powerful tool for gathering a group of followers, motivated by the inherent virtue of the vision rather than by the possibility of pecuniary rewards (Bass and Avolio, 1993). The effect of transformational leadership becomes more exaggerated as one moves up the organisational structure although its effect amongst project managers is still uncertain (Keegan and Den Hartog, 2004; Kissi et al., 2013). This provides additional justification for examining the effect of senior leadership on a project given its exaggerated effect on project outcomes.

Transactional leadership can be considered as a contrast to transformational leadership (Bass, 1990; Rowold, 2006; Tyssen et al., 2013). While transformational leaders tend to gather followers with the aid of their vision, transactional leaders are generally granted authority by their position within the organisational structure and seek to implement tasks within resource constraints (Bass, 1990). Such transactional leaders tend to pursue a strategy of management by exception, whereby they do not interact with subordinates unless output drops below certain minimum expectations (Bass and Avolio, 1993; Rowold, 2006). It appears to be somewhat ineffective in knowledge-intensive industries due to its as it negatively impacts entrepreneurial behaviour which Alsfar considered to be the ability to identify and exploit new opportunities; this may render transactional leadership incompatible with the highly autonomous nature of research and organisations that host LSRIs.

Laissez-faire leadership is the style in which the leader grants full autonomy to the team to determine goals and mechanisms for task implementation (Bass, 1990). This allows the leader to focus fully on other tasks such as securing resources for the rest of the team (Baumgartel, 1956; Andrews and Farris, 1967; Mumford et al., 2002). It is traditionally referred to rather negatively in the literature as being by far the least satisfactory leadership style for team members due to lower output quality and greater levels of disorganisation and frustration amongst the team (**?**). This theory has been somewhat demonstrated on a very short timescale by Breevaart and Zacher (2019).

While laissez-faire leadership fully delegates decision-making to the team, authoritarian leaders fully centralise decisions with the leader, who demands unquestioning obedience to their chosen path (Bass, 1990; Cheung, 2013). This can be a challenging style for teams to work under and it can negatively affect performance and relationships (Schaubroeck et al., 2017), but there can be some benefit to authoritarian leadership. Authoritarian leaders have been identified in the literature as being particularly valuable during a crisis as they can take the necessary but unpopular decisions to re-establish control of the situation (Kidder, 1981; Taubes, 1986; De Mesquita and Siverson, 1995). There is some further sub-structure to this category of leadership with authoritarian leadership often divided into benevolent and punitive forms (Rachlin and Harrower, 1967). The primary distinction between these is whether the authoritarian leader emphasises the possibility of future reward for obedience or punishments for non-compliance (Rachlin and Harrower, 1967). Current work indicates that employees are indeed more receptive to authoritarian leadership if it occurs within a broader organisational culture of benevolence (Ahmad Bodla et al., 2019).

The final category of leadership is democratic leadership, which. can be considered as being midway between authoritarian and laissez-faire leadership. A democratic leader seeks to set general goals and timelines for the team but allows the team to determine how to achieve those goals (Gastil, 1994; Bass, 1990). It can be an effective leadership style but requires buy-in from the collective to facilitate a culture of participative decision-making (López-Roca and Traver-Martí, 2020).

2.4.2 Contingency theory

Contingency theory starts from the premise that leaders and situations can be classified, and the most appropriate leader can be identified and selected for a situation (Fiedler, 1964; Bratton, 2020). It provides a seemingly rational process for the selection of candidates for a research organisation, especially as the needs of the project changes during its lifecycle. There is some research examining megaprojects using a contingency theory perspective (Shenhar and Holzmann, 2017; Söderlund et al., 2017; Gil and Pinto, 2018);however the literature review did not identify any work examining the specific topics of senior leadership or LSRIs using this perspective.

The method for assessing the leader is the Least Preferred Co-worker scale (LPC), where the level of task- and relationship-motivation is assessed (Fiedler et al., 1976). Task-motivated leaders use the parameter of task completion to evaluate performance, using incentives and punishments to drive adherence to plans individual employees not being a typical concern (Fiedler, 1964; Bons and Fiedler, 1976; Fiedler et al., 1976). By contrast, relationship-motivated leaders seek to facilitate team interactions, assuming that internal knowledge interchange will create more effective solutions (Fiedler, 1964).

Three key factors are available for classifying a situation: leader-member relations, task structure, and position power (Fiedler, 1964). Leader-member relations refers to the group dynamic and attitudes toward the leader (Mumford et al., 2000). Leaders with good team relations will likely have have more influence on satisfied, productive followers, while an atmosphere of mutual hostility and poor performance creates poor relations (Wheeless et al., 1984; Clampitt and Downs, 1993; Campbell et al., 2003). Leader-member exchange (LMX) further develops this thinking by expanding the relationship scope to include the influence of the group on the leader (Uhl-Bien, 2006; Sparrowe, 2020).

Task structure, the second tool for assessing the situation, is a measure of work standardisation (Mott, 1971; Gillen and Carroll, 1985). A more standardised task will have set procedures and will be less likely to suffer a schedule slippage; this will suit a task-focussed leader expecting at least certain minimum output levels (Pinto, 2012). Tasks that are less standardised may be better suited to a relationship-motivated leader who promotes a knowledge-sharing environment (Tosi and Tosi, 1976). Since LSRIs appear to embody the characteristics of both technically uncertain projects and megaprojects, suggesting that there may be a low level of task structure and that leaders focus on facilitating the sharing of knowledge rather than adherence to schedules.

Position power is the third factor determining a situation and it describes the powers that the leader has to reward or discipline team members. A leader with a wider range of powers has a greater power in this regard than one whose powers are less wide-ranging (Fiedler, 1964; Bratton, 2020). An individual in a senior leadership position will have greater power to influence the direction of the organisation, but it may take some time for the effects of such decisions to become apparent.

Contingency theory offers the possibilities for an organisation to tailor leadership selection to meet certain phase-specific needs or a leader can adapt their own behaviours to suit a new situation. This naturally raises queries regarding the evolution of a project over its lifetime. Given that LSRI projects may have long lead times between its technical conception and first data acquisition (Riordan et al., 2012), host research organisations may perform a similar leadership assessment exercise when selecting a new senior leader. The lifecycles above may play an important role in determining what characteristics are desirable for the senior leader at that time. Conceptually, both Wheelwright and Clark (1992) and Gluck and Foster (1975) describe a change in leadership style during the project lifecycle from a more laissez-faire or democratic style to an authoritarian one. This is despite the obvious issue that changing a project at late stages may incur significant costs and may not be technically feasible due to cascading consequences across the entire system. Nonetheless this provides some sort of conceptual framework for the research. There is some literature considering the role of leadership is in large complex projects such as LSRIs. Most of this literature uses the 'systems builder' concept as a conceptual framework as developed by Hughes (1979, 2004). Such systems builders, who can be either individual persons, teams, or even entire institutions, primarily seek to manage the interfaces between different systems in an array (Sovacool et al., 2018). It is a particularly prominent concept within traditional infrastructure literature (Davies, 1996; Geels, 2007; Magnusson, 2012; Blomkvist and Larsson, 2013; Manders et al., 2016; Sovacool et al., 2018).

3 Method

When considering the design of this this research there were two broad scientific disciplines with LSRIs that met the budgetary inclusion criteria of an overall spend of least $US 1 billion on the project, namely high energy physics (often referred to as 'particle physics') and space science. One primary concern when considering the types of science to investigate was the 'dual use' nature of space science projects, with militaries playing significant roles whether as clients for the project or as part of the delivery partner consortium. This factor influenced the decision to select cases from particle physics projects. A second practical consideration related to the incidence of LSRIs, because billion-dollar projects do occur rather infrequently. Fortunately, there have been two similar particle physics projects at laboratories that even had an intense rivalry - these are the Tevatron and the Large Hadron Collider (LHC) (Lederman, 1983; Hoddeson et al., 2008; Evans, 2014). Furthermore, these two projects happen to be broadly representative of accelerators in particle physics. The consideration of multiple projects provides the basis for stronger conclusions as a distinction can be made between what is unique to a single LSRI and what may be more generalisable (Yin, 1994). As discussed above, most research investigating LSRIs and 'big science' projects have attempted to build theory using only a single project Florio et al. (2016); Florio and Sirtori (2016); Schopper (2016); D'Ippolito and Rüling (2019). This potentially introduces many of the methodological risks observed by (Yin, 1994) and

The fieldwork underpinning this article was conducted as part of a doctoral study. The cases examined were the Tevatron at Fermi National Accelerator Laboratory (Fermilab) in the United States and the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN) located on the Franco-Swiss border. The selection of case studies was dictated by the need to obtain data in a timely fashion (Yin, 1994; Stake, 2005).

3.1 Data collection and analysis

The primary fieldwork was composed of two phases for each of the two large scale research infrastructures. The first phase comprised archival research, examining documentation including early project proposals, design reports, and project management meeting minutes. This research enabled an appreciation of the internal laboratory context and the identification and triangulation of discussion prompts and claims made by interviewees respectively. The second phase constituted interviews with individuals representing a broad swathe of the laboratory community. These two different research methods allowed triangulating, thereby providing a stronger foundation for the findings while mitigating some of the weaknesses associated with interviewing individuals about events that took place many years in the past. There were sixteen interviews examining the Tevatron at Fermilab and nineteen interviews examining the LHC at CERN. A summary of the interviews including duration, project roles, and which project phases the interviewee was present for is given in Appendix 1.

The analysis was conducted along thematic lines using manual analysis to mitigate the concern that using a discourse or textual analysis might lead to certain 'off-the-cuff' comments, resulting in inaccurate conclusions (Dexter, 2006). The process of coding the interviews began by unifying all comments about a specific topic into a single array; this did occasionally necessitate duplication of statements when one could be considered relevant to two arrays. At this early stage, the Tevatron and LHC fieldwork was kept separate. Following this brief initial coding each statement within an array was essentially distilled into the key theme described. During the analysis many similar themes emerged within a single array and theorised how these themes might relate to LSRI leadership and lifecycles in line with (Yin, 1994); particular consideration was given to the leadership and project activities that took place within each phase to identify where there was overlap and where additional work was conducted that current theory and practice had not yet captured. Where were disputes regarding when certain activities took place, greater credence was given towards primary interview data discussing leadership activities which perhaps represented operationalisation of the project. This was a difficult issue and perhaps represents a limitation of the research. After creating a theory explaining each array, such as the needs of the project at a given point in time and how the senior leader met those needs, each theory was integrated to form a broader understanding of leadership in LSRIs. The final stage in the process was to compare the theories that had emerged from each separate case study to determine what factors were common to both case studies and to examine whether these theories could be explained using existing knowledge. Figure 1 below summarises the data collection and analysis process.

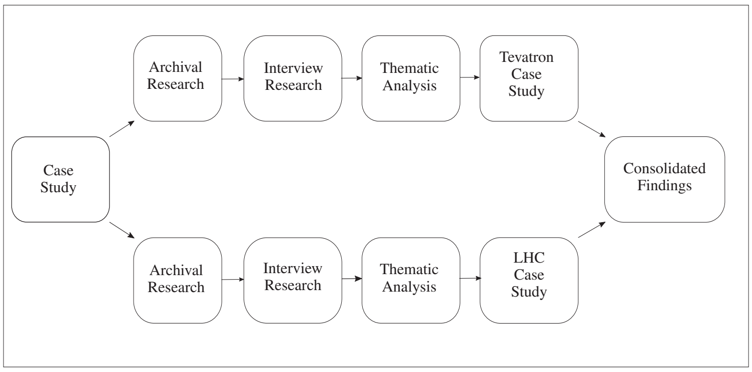

Figure 1: A summary of the data collection and analysis process

4 Findings

This section focusses on a particularly unexpected insight provided by interviewees that emerged during the fieldwork. The interviews revealed a strategy that both Fermilab and CERN tailored senior leadership selection primarily to meet the needs of their project at that specific point in its lifecycle. This trend seemed to be less apparent at Fermilab compared to CERN owing to its different governance arrangements (Hoddeson et al., 2008). Nonetheless, it proved to be a key factor behind the successful construction of the Tevatron.

4.1 Evidence from the Tevatron at Fermilab

The Tevatron at Fermilab was an accelerator constructed in the 1980s, although its foundations can be traced back much further. It could operate in either a fixed target mode[5] or in a collider mode[6] and its opening marked the first use of superconductivity[7] in particle physics (Hoddeson, 1987), allowing the discovery of new particles including the top quark (Collaboration et al., 1995). When operating in collider mode, it could achieve a peak energy in 1 TeV in a centre of mass frame when colliding protons and antiprotons. Its closure in 2011 was hastened by the commissioning of the LHC and the subsequent loss of the 'energy frontier' by the Tevatron (Oddone, 2011; Anon, 2011). At Fermilab, directors are not limited to terms of office, and there is no informal convention that directors must serve for a specified period. This has resulted in directorships ranging from as long as eleven years to as short as six years.

The Tevatron was conceived primarily in response to the new ability of scientists to use superconductivity to create high powered magnetic fields (Hoddeson, 1987). These developments were identified by Wilson during the construction of the original accelerator at Fermilab, the Main Ring (Hoddeson, 1987). These quotes illustrate the popular perception of these events:

> "When Bob [Wilson] arrived, very soon he wanted to build a superconducting ring accelerator. Focussed on building it and the lab." (Source: F6)

And:

[5] This is an operation mode in which the machine accelerated a particle beam before colliding these particles with a stationary particle 'target'.

[6] This is an operation mode where the machine accelerated two counter-rotating beams of particles before colliding these beams. As the beams are orbiting in opposite directions, it is possible to achieve collisions at much higher energies than in a fixed target mode.

[7] This is a physical state in which extremely cold materials achieve a resistance of zero and can therefore carry very high currents.

> "Bob [Wilson] always had a plan for a bigger machine than the Main Ring... when superconductivity appeared on the horizon; Bob [Wilson] noticed its potential and started quietly moving things." (Source: F7)

This new machine, in which the Main Ring would be upgraded to take advantage of superconductivity, was originally identified as the 'Energy Doubler' (Hoddeson et al., 2008). However, while Wilson may have moved funding to take advantage of new developments, socio-political events soon became the more pressing issue (Hoddeson et al., 2008). This shift in relative importance can be linked to the 1970's Oil Crisis, which led to a major re-organisation of the US science policy landscape where the US national laboratory system transitioned from being administered by the Atomic Energy Commission (AEC) to the new Department of Energy. This coincided with a change in public attitudes toward science and now scientists felt forced to 'compete' with other areas of the federal budget. Wilson was more accustomed to the old funding methods under the AEC where technological novelty was one of the primary determinants for a successful funding bid:

> "Bob [Wilson] would build with the assumption that if you build it, then the experimental ideas will come. His [Wilson's] main metric for measuring success was machine performance." (Source: F4)

As discussed above, Interviewee F11 described Wilson as having an attitude in which novel technology could solely justify investment. But his attitude was not just ill-suited to the times but according to F11, he was also ill-suited to meeting the Tevatron's needs at this stage:

> "He [Bob Wilson] was the best project initiator but not the best listener. Despite his forceful nature, he was very laissez-faire when it came to other things." (Source: F11)

A copy of Wilson's resignation letter reveals his concerns about the US funding for the Tevatron, particularly in comparison to the significant financial resources that were available to CERN (Anon, 1978). Wilson directly linked his decision to resign to the President Carter's fiscal year 1979 budget proposal, which allocated only a small inflationary increase to the budget. Wilson and the various funding agencies had a long history of difficult relations dating back at least to the early days of Fermilab, as the quote from Interviewee F7 demonstrates:

> "Bob (Wilson) had saved $20 million from building the lab which he felt was his..." (Source: F7)

This attitude can be seen as contrasting with the reasonable premise that savings from a project might be reimbursed to the funding agency. This is particularly applicable to an era of restraint in science budgets. However, Wilson's ability to convince people to come together to help him achieve his goals for the laboratory made him ideal to be the leader during the initial construction of the laboratory, where there would have been many new employees with the potential for unification under the umbrella of his vision. Likewise, his charisma allowed him to persuade others to push themselves to achieve the seemingly impossible. In the words of Interviewee F5:

> "Bob [Wilson] was a leader and a father figure. As his leaving gift he built a sculpture and had welders teach him how to weld, even though he wasn't in the union; he was just so nice people wanted to help him. You even needed his approval to cut down trees on-site as he wanted to re-create the frontier." (Source: F5)

Following Wilson's departure, a new Fermilab director, Leon Lederman - originally from Columbia University - was selected. This provides an opportunity to examine whether this new director might have been more suited to meet the changed needs of the Tevatron than Wilson. Lederman took very different approaches to DOE and running the laboratory, as observed by the interviewees. He was observed to be delegating far more than Wilson. Interviewee F5 best described the change from Wilson to Lederman:

> "It was a change in leader from a builder to an experimenter. He ... was a good delegator but also knew how to set guidelines and parameters." (Source: F5)

This represented a shift in leadership style from the somewhat authoritarian Wilson to a democratic Lederman, Interviewee F4, who had also described Wilson as a builder, also categorised Lederman:

> "Leon [Lederman] had ideas about how to experiment on it [the machine] while building." (Source: F4)

Interviewees F10 and F4 also described how Lederman, although not the builder of an institution, understood how to run an existing research institution and optimise it for conducting research:

> "Leon [Lederman] wasn't a manager but he really knew how to pump out physics, even then he'd rather talk physics than policy." (Source: F10)

And:

> "He [Lederman] took the Fermilab that Bob [Wilson] built and put it on a course with more focus." (Source: F4)

As a result of these new governance arrangements Lederman did not transfer the directorship to meet the changed needs for the next phase, that of construction. But Lederman did account for this change in phase by transitioning to an oversight role and delegating most of the authority to three project managers. This clearly visible in the minutes of the project management meetings from that time. There, while Lederman did delegate substantially, he did retain the right to make key technical decisions. In the early meetings for one of the Tevatron projects there were four potential technologies that were available for the generation of antiprotons:

> "(1) A precooler cooler design with all the antiprotons you could ask for,
> (2) An all-stochastic antiproton cooling scheme,
> (3) A boxcar stacking of antiprotons in a smaller precooler ring,
> (4) Antiproton deceleration and cooling in a set of four rings.
> When asked what happens at the end of the day, Leon [Lederman] said 'I make a decision'." (Source: Project Management Group Meeting Minutes from November 21, 1980)

This is also supported by statements from F2:

> "Democratic leaders may give the impression of democracy, but this may not be a reality. But it's useful to appear to be one, but steer when necessary. He (Lederman) would listen but take his own counsel and decide for himself." (Source: F2)

These observations suggest that directors play vital roles in discrete phases in the life of an LSRI project. Wilson helped in the conception of the Tevatron, guiding it through early life and making important technical decisions, thereby showing authoritarian tendencies. However, Wilson was not particularly well-suited to securing funding in the new environment of the 1970's because of his attitude that novel technology by itself justified funding. Lederman could better engage with stakeholders to secure funding and command the confidence of these now budget-conscious government agencies before delegating most of the authority for construction to project managers while reserving some key decisions.

4.2 Evidence from the Large Hadron Collider at CERN

The LHC at CERN, which commenced operation in 2008 is currently the highest energy particle collider in the world (CERN, 2016). At the time of writing (2020), it is currently in a prolonged shutdown for upgrades to the magnet and cryogenics systems but during its two previous operating 'runs' sufficient data were created to allow scientists to confirm the existence of the Higgs boson, one of the fundamental constituents of matter (Aad et al., 2012; Riordan et al., 2012). The construction of the LHC was a major shift in CERN's culture; Martin and Irvine (1984a) had previously queried choice to build technologically conservative and expensive machines that could not be used to make new particle discoveries. The LHC marked a shift in CERN towards constructing much more innovative designs that could be used to discover new particles. During its early stages, one of the key champions for the LHC was Carlo Rubbia, who has been extensively examined for his distinctively authoritarian leadership style (Krige, 2001b,a; Taubes, 2003). Due to its status as an intergovernmental organisation, one of CERN's more unusual institutional policies is that the Director-General as the senior leader of the organisation serves a single five-year term[8] (Hermann et al., 1987b,a; Krige et al., 1997). This provided the possibility of tailoring Director-General selection according to the medium-term needs of the construction project.

The observation that Directors-General had differing goals to fulfil during their tenures first emerged during the fieldwork at Fermilab, with Interviewee F7 :

> "At CERN the LHC effectively ran the lab. Each DG was selected to suit the needs of the project, building then upgrading; [I] bet that there'll be a data miner next." (Source: F7)

About half of the interviewees said that the tradition that a CERN Director-General served a single five-year term provided this opportunity as seen below:

[8]It is noted that Fabiola Gianotti has recently been appointed to a second five-year term as CERN Director-General. But this is an exception to the historic norm.

> “There were four DGs [Directors General] over the life of LHC, all very suited to the period [of time] and part of the project” (Source: C1)

And:

> “You need transformational leadership at some point in the project lifecycle, a [Robert] Wilson-esque person [the first director of Fermilab]. The vision to do something great. At other times, it’s useless. The R&D phase requires a different leader and you become more transactional or democratic toward the end stages.” (Source: C15)

And:

> “The definition of success varies between leaders.” (Source: C16)

It is noteworthy that Interviewee C15 described the need for a ‘Wilson-esque’ leader at the early stage to craft the vision for the project. This also highlights a leadership trajectory that conflicts with the literature as the literature indicates that leadership becomes less democratic, not more, towards project end stages.

4.2.1 Carlo Rubbia

Carlo Rubbia served as Director-General in the early years of the LHC; during this period, he became personally involved in many of the discussions concerning the LHC. These included defending the LHC from attacks regarding its value compared to alternative options (Fraser, 1997; Smith, 2007).

Approximately three quarters of the interviewees described instances of personal contact with Rubbia, while the remaining quarter knew him by reputation. All comments featured two obvious themes about Rubbia relating to his strongly authoritarian leadership style coupled with his technical competence. Two interviewees even suggested that because of his ability to marshal resources to ensure success as described by Krige (2001b), he dominated CERN to such the extent that the entire organisation became dependent on him:

> “I knew his reputation, but the meeting of the directorate was incredible as they were like mice around him.” (Source: C4)

And:

> “You could never grow a leader like him using a textbook [but] I could see the culture of fear he left" (Source: C2)

These quotes demonstrate the ability of Rubbia to propose new experiments and shepherd the LHC concept through the early stages thanks to what interviewees described as his genius and his authoritarian character. This is clear from Taubes (1986, 2003) as well as from the quotes below:

> “Carlo Rubbia was ingenious, had many ideas, and knew how to structure his thinking.” (Source: C12)

And:

> “As far from real management as you could get, everyone loved him, but he was hell to work with. Charismatic, unpredictable. Carlo Rubbia could destroy you if you weren’t of strong character. Almost alienated people but still putting out whacky ideas even now!” (Source: C1)

And:

> “I’ve been personally squeezed by Carlo, he’s brilliant. On Christmas Eve one year I was about to leave CERN at 7pm when he sends over a four-page proposal to push for a muon collider. Brilliant mind.” (Source: C5)

However, Interviewee C6’s quote shows that Rubbia tended to lose interest in any single proposed experiment or project. This indicates an essential similarity between the styles of Rubbia and Wilson. In both cases, the interviewees at their respective laboratories considered them excellent project initiators but less adept at closing projects.

4.2.2 Christopher Llewellyn-Smith

Christopher Llewellyn-Smith was the second Director-General over the LHC construction period. During his term, the CERN Council formally approved the LHC as a two-stage project and, as a result of creative funding mechanisms devised by CERN management, converted this approval to a single-stage project. When asked about Llewellyn-Smith's purpose in relation to the LHC, almost all interviewees stated that his success was in taking Rubbia's vision and turning it into something that was realistically workable, as described by Interviewee C6:

> "...a great DG for getting LHC approved. Required a lot of deal making, he was definitely the right person at the right time." (Source: C6)

Effectively the change was from what machine to how to build a specific one. Interviewee C1 described how the change in style Rubbia and Llewellyn-Smith unlocked new ways to secure support for the LHC:

> "Carlo Rubbia was more confrontational but when Christopher Llewellyn-Smith came in, the doors just opened for this polite English gentleman. ... His management style is to like structure." (Source: C1)

The statement from Interviewee C1 that Llewellyn-Smith "liked structure" illustrates that during this time, CERN transitioned from being heavily dependent on a single charismatic leader back to a more traditional structure with clearly defined roles and operating procedures. Llewellyn-Smith delegated to others and provided oversight over these various activities. This contrasts with Rubbia's more direct role and represents both Llewellyn-Smith's more transactional leadership style and the breadth of work required. The interviewees expressed no agreed view regarding Llewellyn-Smith's leadership style. There was a wide range of categorisations, with most of them describing Llewellyn-Smith as primarily a mix of transformational and democratic leadership, although two interviewees also categorised Llewellyn-Smith to a lesser extent as transactional. The introduction of more transactional leadership is in line with the literature that leaders tend to become more transactional as the project progresses (Frame, 1987; Turner, 1999). However, rather than the leader changing behaviour, as the literature suggests (Tracey and Hinkin, 1998), the findings indicate that it is better for the project to select a new senior leader who embodies the desired attitudes to manage this new situation.

4.2.3 Luciano Maiani

Luciano Maiani was the third Director-General of the LHC during its construction and, during his term, much of the construction was completed. Roughly three quarters of the interviewees described the laboratory atmosphere during this time as solely focussed on constructing the LHC. This can be evidenced by the decision of CERN management to shut down the CERN accelerator complex in order to free up resources for the LHC (Abbott, 2002a). The LHC project leader, Lyndon Evans, was allowed enough autonomy to run the project as necessary. The organisational structure of CERN was even temporarily changed to a matrix style with the project cutting across the traditional departments, sections, and groups (Lebrun and Taylor, 2017). The role of CERN management was to track the project and maintain the confidence of the Council in the project. Only a single interviewee described Maiani specifically:

> "We had Christopher Llewellyn-Smith and Carlo Rubbia in the late 80s and 90s, what about after that? Luciano Maiani was less organised, less democratic, more authoritarian. He didn't discuss so much." (Source: C6)

This may not be such a surprising assessment, considering that the laboratory was then focussed on building the LHC, with most of the technological problems solved. Then the project could be managed in a more traditional manner, focussing on cost-control and remaining on schedule. Unfortunately, during 2001, a re-calibration of the budget to account for changes in the wider economic environment revealed that the 1990s projected costings had been extremely optimistic and a budget gap of around 700 MCHF had developed (Adam, 2001). Widespread changes were introduced to the accounting and operating procedures at CERN in exchange for the additional 400MCHF from Member States to reassure the CERN Council that LHC spending was under control. These included the introduction of a new accounting method, Earned Value Management and even the temporary shutdown of the CERN accelerator complex to free up resources (Abbott, 2002b).

Maiani's characteristics as a leader resembled those of Llewellyn-Smith considered above. Both were more transactional than Rubbia, but while Llewellyn-Smith was democratic, Maiani's tenure marked a return to a somewhat authoritarian style of leadership at CERN. However, none of the interviewees described Maiani as being as authoritarian as Rubbia, contrasting the benevolent Maiani with that of the punitive Rubbia. When there were issues, such as the 2001 budget crisis, Maiani intervened to maintain the trust of the Council and demonstrate that the project was under control. He exhibited similar diplomatic abilities to Llewellyn-Smith but aimed at different goals.

4.2.4 Robert Aymar

Robert Aymar was the fourth and final Director-General during the phase of LHC construction, moving from his previous role as President of the CERN Council. During his time as Director-General the LHC was completed, although there was a magnet quench incident soon after the LHC achieved first beam circulation which damaged equipment and delayed full operation of the LHC (CERN, 2008). Aymar was categorised by every interviewee as being more authoritarian than the other Directors-General by the five interviewees who were willing to discuss him. Three interviewees even suggested that he was not a true member of the CERN community, as exemplified by Interviewee C6's quote:

> "Aymar was definitely authoritarian, like a General as he was one . It doesn't work in high energy physics so there was a cultural conflict." (Source: C6)

He was also rather dismissively referred to C16 as:

> "...essentially a manager. He pushed for collisions without tests." (Source: C16)

The quote from Interviewee C6 may not be surprising given that the literature tends to view authoritarians positively at the end stages of a project when the main technologies should be well-understood. Aymar exhibited similar characteristics to Maiani, being both transactional and authoritarian. However, seemed to grate with the CERN community, as illustrated by the comments above, indicating that a different approach might have been more successful.

4.3 LSRI phases

This section firstly examines the LSRI phases that emerged from the fieldwork. As Fermilab and CERN had relatively more leeway to organise the construction of their respective machines as they saw expedient compared to other megaprojects, their respective lifecycles were slightly different to those identified in Section 2.3. The second part of this section draws upon the evidence and relevant theory to answer the first and second research questions which are **"do these LSRIs fit established the lifecycle models?"** and **"if so, which model provides the best fit?"**. The third part of this section addresses the third research question, **"how does senior leadership adapt as the project moves through its lifecycle?"**. The finding that the selection of different leaders is partly linked to a particular project phase suggests that selection panels have effectively adopted a contingency theory framework for senior leadership selection; whether this has been as a result of deliberate decisions cannot be determined due to the 'black box' nature of recruitment and selection. There appear to be common phases within the lifetimes of the two LSRIs investigated.

4.3.1 Initiation

This is the first phase of the project, where many technical options are explored and eventually narrowed down to a single LSRI technical design which forms the basis for the LSRI project. Even during this early stage, senior leaders are involved in making decisions, particularly when changes in one sub-system of the project may have cascading consequences across the entire array of systems. A senior leader will need the conceptual and political skills to understand issues relating to different systems and manage these risks appropriately. Once the LSRI has a fixed design, the senior leader seeks to secure the LSRIs place within future strategy. Research institutions tend to recruit charismatic authoritarian senior leaders during this time to take these decisions and unite the workforce.

4.3.2 Approval

The second phase of the project builds on the previous phase to develop the project beyond a concept into a feasible reality. A senior leader must further engage with stakeholders to secure funding for the project as well as to develop mechanisms that will allow progress and quality to be measured. In some cases, the negotiation of novel funding or diplomatic agreements to render the project feasible. During this time, there is a transition in leadership to a more democratic style.

4.3.3 Construction

This is the third phase of the construction project where a senior leader generally does not directly manage the project. Instead, the project leader or manager will provide day-to-day management of the project, and senior involvement only occurs if stakeholder trust is at risk. In these situations, the senior leader must intervene but the scientific community perceives this as someone reluctantly stepping in to avert a greater crisis.

4.3.4 Exploitation

This fourth and final phase begins as the LSRI starts operation. During this time, the focus shifts to supporting experimental collaborations during first data acquisitions and system optimisation and upgrades. The second, horizon scanning, involves looking towards the future and the next big machine. Although senior leaders generally do not lead these efforts, they support it by allocating resources from within the normal laboratory operating budget. Eventually a new leader emerges and crafts a new vision for this new LSRI, and the cycle will begin again.

4.4 Research Question 3: how does leadership adapt as the project moves through its lifecycle?

A summary of each project's phases and the characteristics of the phase-specific senior leader can be seen in Table 2.

Table 2: A summary of the characteristics of each phase during the Tevatron and LHC construction and the respective characteristics of the senior leader

	Characteristics of phase		Characteristics of phase-specific senior leader	
Phase	Tevatron (Fermilab)	LHC (CERN)	Tevatron (Fermilab)	LHC (CERN)
Initiation	Superconductivity identified as promising technology. Laboratory budget funds R&D	Previous accelerator completed. Possibility of augmenting it with a Large Hadron Collider. Rubbia provides strong support	Transformational. Authoritarian	Transformational. Authoritarian
Approval	Wilson resigns after failure to secure funding. Leon Lederman becomes new director. Uses new strategy to secure Tevatron funding	Rubbia's term as DG ends. Llewellyn-Smith builds agreements amongst international community	Initially transformational and authoritarian. Later more democratic	More democratic and consensus driven
Construction	Lederman remains director. Most project responsibility handed to three project leaders. Lederman provides oversight	Llewellyn-Smith's DG term ends. Maiani and later Aymar provide oversight over the project leader (Lyndon Evans)	No director change, heavily delegation represents a more laissez-faire style	Relatively laissez-faire but reserving right to intervene
Exploitation	Laboratory community uses new machine. Community begins designs for next big machine.	'First physics' during Aymar term. Upgrades during subsequent Director-Generalships. Community coalescing around next big machine.	Continuing to be laissez-faire. Supporting future community needs	Continuing to be laissez-faire. Supporting future community needs

A consolidated summary of the characteristics of the phases and how senior leadership shifts can be found in Table 3. This answers Research Question 3 **how does leadership adapt as the project moves through its lifecycle?**:

5 Discussion

This section draws upon the evidence and relevant theory to answer and discuss the first and second research questions which are **"do these LSRIs fit established the lifecycle models?"** and **"if so, which model provides the best fit?"**. The third part of this section addresses the third research question, **"how does senior leadership adapt as the project moves through its lifecycle?"**.

Table 3: A summary of the phases identified for LSRIs and the characteristics of the phase-specific senior leader

Phase	Characteristics of phase	Characteristics of phase-specific senior leader
Initiation	Many technical ambiguities Internal debate over which big machine should form basis of laboratory strategy	Authoritarian. Technically focussed Very charismatic. Transformational or authoritarian leaders preferred by institutions
Approval	Internal debate settled around machine. Funding required which necessitates agreement amongst stakeholders	Democratic. Consultative. Seeking to build consensus amongst stakeholders
Construction	Construction and civil engineering Machine assembled. Project leader takes lead and has freedom to be authoritarian as necessary	Oversight of the project leader. Rarely intervenes except in the event of a major crisis which risks loss of stakeholder trust
Exploitation	Shift in focus: a) Full exploitation of the completed LSRI b) Horizon scanning to determine the characteristics of the next generation of LSRI	Support role to help the laboratory and collaborations generate data. Moving resources to help individuals investigate promising technologies for the next big machine.

A re-examination of the literature considering these findings suggests that the concept of selecting research organisation senior leaders with the specific intention that they will meet the phase-specific needs of the project is difficult to explain using the style paradigm of leadership. The Analysis of this information using the style paradigm would indicate that the senior leader could simply change their leadership style as the project progresses (Bass, 1990). This would have the benefit of continuity of leadership the laboratory builds the machine. However, substitution of the senior leader for an alternative one does not fit the style paradigm. Contingency theory does offer a potential explanation for this trend (Fiedler, 1964). This theory proposes that it is possible to classify a leader and situation using the tools outlined above in the literature review section.

5.1 Research Questions 1 and 2: "do these LSRIs fit established the lifecycle models?" and "if so which model provides the best fit?"

The first finding is presented in Table 2, which maps the LSRI project phases identified against the four models from Table 1. While LSRI project phases do not map perfectly onto any of the lifecycle models, they map onto the traditional project lifecycle model rather better than either the Wheelwright and Clark (1992) or Gluck and Foster (1975) models. However, the exploitation phase that begins after the commissioning of the LSRI does not map neatly onto any of the models because it occurs after project completion. A second finding that is somewhat in conflict with previous literature is the observation that senior leaders of research organisations tend to get involved in detailed technical decisions at the early stages of LSRIs, and this level of involvement generally declines as the project proceeds. This contrasts with the literature which reports that managers, particularly of development projects, do not get involved in early technical discussions but exercise substantial influence towards the end of the project (Gluck and Foster, 1975; Wheelwright and Clark, 1992). This is despite the issue that such involvement at end-stages would be at a time when their ability to influence the final project is limited (Gluck and Foster, 1975; Wheelwright and Clark, 1992).

On balance, this contrast results from the deep technical competence that characterises of LSRI leadership. During the initiation phase, there are many ambiguities and an LSRI project lacks an appointed project leader/manager. Therefore, authoritarian senior leaders perceive and act on the need to be part of these detailed technical discussions, even if their proposals require amendment at a later point. This was notably the case for both Robert Wilson at the Tevatron and Carlo Rubbia at the LHC.

In relation to the lifecycle models used by policymakers, specifically those models used by NSF and ESFRI , there is significant similarity. Notably the NSF and ESFRI phases of 'Construction' and 'Implementation' overlap almost exactly with the LSRI 'Construction' phase. However, the most significant difference between models used by funding agencies and the lifecycle that scientists have devised seems to be the broad range of activities conducted during the final phases. While policymakers focus on divesting from the project, researchers refocus their attention toward the next big machine, which means that particle physicists seem to be in a constant state of construction. This is likely more a reflection of particle physics laboratories which tend to incorporate older machines into the support infrastructure of the new generation which may not be possible with other types of LSRI. This horizon scanning process also seems to look much further into the future than current policy of 30 and ten years respectively (Baker, 2016; Burrows, 2017; ESFRI, 2018; Hofstadter et al., 2019). This potentially represents an opportunity for policymakers to capture these 'bottom-up' community practices by commissioning a 'generational survey' upon completing an LSRI.

The answers to the first and second research questions are that LSRIs do fit these established lifecycle models and that the LSRI lifecycle fits the traditional project lifecycle model rather better than either the Wheelwright and Clark (1992) or Gluck and Foster (1975) models. However, of the models used in policy, the large facility lifecycle model used by NSF captures the LSRI lifecycle rather better in its 'Divestment' phase compared to ESFRI as it implies the feasibility of incorporating one project into the supporting infrastructure of its successor. Table 2 comprises a mapping of the several lifecycle models from literature and practice mapping onto the corresponding LSRI project phases.

These findings partially conflict with previous literature, in that it is revealed that senior leaders tend to get involved in detailed technical decisions at the early stages of LSRIs and this level of involvement generally declines as the project proceeds. This is in with the literature Prior literature states that managers do not get involved in early technical discussions but rather exercise substantial influence at project end-stages (Gluck and Foster, 1975; Wheelwright and Clark, 1992). This conflict between the literature and the findings is likely a product of the deep level of technical competence that is characteristic of leadership in LSRIs.

The appointment of the LSRI project leader, which usually occurs during the approval phase, is a pivotal moment that marks the senior leader's transition of the senior leader to an oversight role, focussing on the interfaces between systems in the array rather than individual systems. A senior leader will normally only get involved with the LSRI project if a major crisis arises that threatens stakeholder confidence. Therefore, the answer to Research Question 3 is that senior leadership begins as quite authoritarian with the senior leader unusually getting involved in technical minutiae. As the

Table 4: A summary of the development project phases proposed by Wheelwright (1992) and Gluck and Foster (1975) respectively mapped onto the traditional project lifecycle and lifecycle models used by NSF, ESFRI, and US DOE including the LSRI phases identified by this research

<table>
<tr><th>Project lifecycle</th><th>Wheelwright (1992) model</th><th>Gluck and Foster (1975) model</th><th>Large facility lifecycle (NSF)</th><th>ESFRI lifecycle</th><th>Typical DOE acquisition management system</th><th>LSRI phases</th></tr>
<tr><td>Conceptual</td><td>Knowledge acquisition</td><td>Study</td><td>Development</td><td>Concept development</td><td>Initiation</td><td rowspan="2">Initiation</td></tr>
<tr><td>Planning</td><td>Concept investigation</td><td rowspan="2">Design</td><td rowspan="3">Design</td><td rowspan="2">Design</td><td rowspan="3">Definition</td></tr>
<tr><td rowspan="3">Execution</td><td>Basic design</td><td rowspan="2">Approval</td></tr>
<tr><td>Prototype building</td><td>Development</td><td>Preparation</td></tr>
<tr><td>Pilot production</td><td>Preproduction</td><td rowspan="2">Construction</td><td rowspan="2">Implementation</td><td>Execution</td><td rowspan="2">Construction</td></tr>
<tr><td>Termination</td><td>Manufacturing ramp-up</td><td>Production</td><td>Closeout</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td>Operation</td><td>Operation</td><td rowspan="2"></td><td rowspan="2">Exploitation</td></tr>
<tr><td>Divestment</td><td>Termination</td></tr>
</table>

project moves through its lifecycle, a new leader is substituted, resulting in a transition to an increasingly democratic style of leadership. This finding contrasts with prior literature which indicates the reverse trend is more prevalent (Gluck and Foster, 1975; Frame, 1987; Wheelwright and Clark, 1992).

6 Conclusions, implications, and opportunities for future work

Each of these LSRI projects appeared to dominate the parent research organisation to such an extent that selection of senior leadership was heavily influenced by the needs of the project. When given the freedom to structure their projects as they see fit, scientists in particle physics tend to organise LSRIs according to a four-phase lifecycle with each phase corresponding to the five-year tenure of a senior leader. These phases have been described as: Initiation, Approval, Construction, and Exploitation. These phases map onto the traditional project and the NSF large facility lifecycles better than the other models described in this chapter. As the LSRI project moves through its lifecycle, the characteristics of leaders change from authoritarian to increasingly democratic style. This contrasts with prior literature that describes leadership style transition in reverse – from democratic to authoritarian. This likely results from the high technology nature of LSRIs, coupled with the unusual factor that the technical competence to design all the systems is available 'in-house'.

This article makes contributions to leadership theory and to LSRI domain by demonstrating that it is possible to apply contingency theory to empirical leadership evidence. In terms of LSRIs, this article takes the Qiao et al. (2016) definition of LSRIs and draws on the relevant project management literature to provide more robust inclusion criteria for future work. More precisely, LSRIs can be considered to be a sub-category of megaprojects that incorporate a high or very high level of technological uncertainty (Shenhar and Dvir, 1996; Flyvbjerg et al., 2003). These LSRIs exhibit lifecycles that map onto traditional project lifecycles rather well although the level of management attention given to them conflicts with the existing literature.

Research organisations embarking on LSRI construction projects may wish to emulate this strategy. However, it requires governance arrangements, including the implementation of specific 5-year term limits for senior leaders. Such a selection process could also include a formalised assessment of the project needs over the next five years using a contingency theory framework (Fiedler, 1964), a well-embedded concept in particle physics, and as currently applied to the 'European Strategy for High Energy Physics' where it acts as a formalised assessment for the European landscape.

In a more generalised sense, the findings are of value to other types of megaprojects and large organisations in the private sector. The notion of applying contingency theory to senior leadership selection does not seem to be particularly innovative. However, it appears to be notably absent in both literature and practice that is limited to noting the importance of leadership alignment with broader factors such as culture (Taylor and Taylor, 2013); this article begins to address the next logical steps of this topic, namely how leadership can be brought into alignment with overall strategy. This could be readily applied in the case of senior organisational leadership but may more challenging in the case of megaprojects as due to the temporary nature of delivery partner organisations (Davies et al., 2019). It would also require a significant change in attitude towards senior leadership departures; currently the substitution of a leader is often presented in the literature as a failure (Graen and Ginsburgh, 1977; van Marrewijk et al., 2008). For such a strategy to be acceptable in the future, the notion of resignation will need re-framing from admitting failure towards the creation of a better fit between the leader and a changed situation.

Funders and policymakers may also wish to capture the 'bottom up' community assessments that occur once an LSRI has been completed. Current policy usually assesses community needs within a two-, five-, or ten-year timeframe (Baker, 2016; ESFRI, 2018; Hofstadter et al., 2019), whereas the community uses a timeframe as long as 30 years. It may therefore be desirable to introduce a new 'generational survey' upon completing an LSRI project to incorporate the community's very long-term needs into research strategy.

One potential issue from this research regards its generalisability. Although there was a conscious decision to investigate two different but related projects, one might reasonably argue that these two projects alone are still an unreliable foundation for new theory. However, the real impact of LSRIs lies in their size rather than in their frequency - their substantial cost means that, despite their small numbers, they can have a disproportionate impact on government budgets.

Several opportunities present themselves for further research. First is to both deepen and diversify this research elsewhere within the research infrastructure domain. In addition to expanding the study to include more cases within particle physics, there is also the possibility of investigating different types of research infrastructure which may employ different leadership selection techniques (ESFRI, 2018). It may also be valuable to repeat the study in other areas such as infrastructure construction and the energy extraction industries to determine whether this phasing phenomenon is unique to LSRI construction projects or can be further generalised.

A Appendix 1

Table 5: Summary of interview data collection (Winter 2014 - Summer 2015)

Main focus of discussion (Tevatron/LHC)	Project phase that interviewee was present for	Interviewee function	Interview date	Interview duration	Was the interviewee involved in the 'other' project? (Y/N)	Project phase that interviewee was present for in the 'other' project	Interviewee function in the other project
Tevatron	Construction, Exploitation	Experimental collaborator, later engineer within Tevatron project	20 January 2014	60 Mins	N		
Tevatron	Construction, Exploitation	Group leader, project manager, head of division	22 January 2014	90 mins	N		
Tevatron	All phases	Deputy director	27 January 2014	45 mins	N		
Tevatron	Approval, Construction, Exploitation	Project manager, head of division	28 January 2014	90 mins	N		
Tevatron	Approval, Construction, Exploitation	Project manager, director	30 January 2014	150 mins	N		
Tevatron	All phases	HR specialist	31 January 2014	120 mins	N		
Tevatron	All phases	Project manager	3 February 2014	90 mins	N		
Tevatron	All phases	Accelerator designer/engineer	4 February 2014	60 mins	N		
Tevatron	Construction, Exploitation	Experimentalist	4 February 2014	90 mins	N		
Tevatron	Construction, Exploitation	Team leader, later project manager	5 February 2014	60 mins	Y	Construction, Exploitation	Head of collaboration board
Tevatron	Construction, Exploitation	Engineer, later project manager	7 February 2014	60 mins	Y	Construction, Exploitation	Experimentalist leader
Tevatron	Exploitation	Team leader	10 December 2014	60 mins	Y	Construction, Exploitation	Project leader, later experimental spokesperson
Tevatron	Exploitation	Team leader	23 February 2015	60 mins	Y	Construction, Exploitation	Team leader, later Director-General at different laboratory
LHC	All phases	Project manager	2 February 2015	60 mins	Y	Exploitation	Working in problem-focussed teams
LHC	Construction, exploitation	Senior experimental collaborator	6 February 2015	60 mins	N		
LHC	All phases	Project manager	9 February 2015	60 mins	Y	Construction, Exploitation	Accelerator designer
LHC	All phases	Former project manager, now working across laboratory	10 February 2015	60 mins	N		
LHC	All phases (particular emphasis on construction and exploitation)	Senior experimental collaborator	10 February 2015	90 mins	N		
LHC	All phases (particular emphasis on conception and approval)	Theoretical physicist	12 February 2015	90 mins	N		
LHC	Construction, exploitation	Senior experimental collaborator (previous experience working in accelerator construction)	13 February 2015	90 mins	Y	Exploitation	Working in problem-focussed teams
LHC	All phases	Former senior experimental collaborator (now leading an analytical team)	18 February 2015	60 mins	N		
LHC	Construction, Exploitation	Experimental collaborator working closely with LHC project team	2 March 2015	90 mins	N		
LHC	Approval, Construction	Project manager	11 March 2015	90 mins	N		
LHC	All phases	Project manager	13 March 2015	90 mins	N		
LHC	Approval	Former senior leader	19 March 2015	120 mins	N		
LHC	Construction, Exploitation	Division leader	24 March 2015	60 mins	N		
LHC	Construction, Exploitation	Experimental project manager	15 April 2015	60 mins	N		
LHC	Construction	Former senior leader	24 June 2015	120 mins	N		

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